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NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

HOLOGRAPHIC INVESTIGATION OF SOLID
PROPELLANT COMBUSTION PARTICLES

by

Peter J. Mellin

December 1983

Thesis Advisor:

D. W. Netzer

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Holographic Investigation of Solid
Propellant Combustion Particles

by

Peter J. Mellin
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1971

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1983

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ABSTRACT

This investigation continued the development of a method for obtaining high quality holograms of the combustion products from aluminized solid rocket motor propellants burned in a two-dimensional motor to provide a cross-flow environment. The use of glass side plates as a motor casing provided both a convenient construction technique and allowed good quality holograms to be obtained. At combustion pressures above 500 psia and propellant slab thicknesses greater than 0.080 inches, the timing of the laser pulse during the burn was found to be critical, since an extremely short time interval existed between the establishment of steady state slab burning and the generation of too much smoke/combustion products to permit laser penetration. As desired operating pressures increase and aluminum powder particle sizes decrease, it will probably be necessary to use thinner propellant slabs.

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I. INTRODUCTION

Although solid propellant rocket motors have had significant performance advances during the past few years, a continuing need exists for even greater improvement. Requirements for heavier payloads, longer ranges and expanded flight envelopes underscore the need for higher performance, i.e., the highest possible specific impulse (I_{sp}).

Metal additives, specifically aluminum, have been used when exhaust smoke is not a problem because their high energy content provides both higher combustion temperatures and a general improvement in specific impulse over non-metallized propellants. In order to realize the full benefit of aluminum additives, all of the available thermal energy must be released and the flow losses minimized. To meet the first condition, an optimum combination of metallic powder particle size, propellant composition and motor geometry must be chosen such that the metallic particles are completely burned to aluminum oxide prior to exiting the combustion chamber. Large particles may still be burning after exiting the combustion chamber if residence times are less than approximately 10-15 msec, resulting in lost energy.

Two-phase flow losses in the nozzle expansion process result from (1) the particles moving slower than the exhaust gases, (2) the particles being cooler than the exhaust gases, and (3) the particles being unable to expand with the expanding gas in the nozzle. To minimize these losses, the particle sizes in the expansion process must be as small as possible. Some two-phase flow loss is unavoidable since the minimum aluminum oxide particle diameters are typically 0.5-2 μm .

Another benefit of metal additives is their effectiveness in dampening the transverse modes of pressure oscillations in the combustion chamber. The latter can result in high chamber pressures and/or motor failure. The frequencies dampened are a function of both the particle size and density.

The objective of this thesis was to continue the development of a simple, reliable method for holographic observation of particle behavior in an environment similar to that found in the port of an actual solid rocket motor. To duplicate motor cross-flow conditions, a 2-D motor which used horizontally opposed slabs was selected. Pressures to 500 psia and slab thickness to 3mm were the goals.

For the exposed scene (the chamber volume illuminated by the laser beam), a hologram provides both amplitude

(as in conventional photography) and phase information. The latter characteristic enables a 3-D image to be reconstructed so that particle behavior in the entire depth of field of the combustion chamber may be recorded. The flame envelope surrounding the burning particles can be eliminated with a narrow pass filter located between the scene and the holographic plate.

Single pulsed holography provides a means for effectively stopping the motion. However, it only provides information during a single instant of time.

II. NATURE OF THE PROBLEM

As stated in the Introduction, the objective of this thesis was to obtain a simple, inexpensive and reliable method for recording particulate behavior under realistic temperature, pressure and cross-flow conditions. Smoke generation (i.e., small Al_2O_3 and binder products, etc.) during the combustion process is a major obstacle, and consists of two distinct but related problems.

The first is that a laser can only penetrate a finite amount of smoke, and the second involves the required scene beam to reference beam illumination ratio. To obtain a high-quality hologram, the illumination ratio reaching the holographic plate should be between 5-10:1. Test-to-test variation of the amount of smoke in the beam path can significantly affect this ratio. To achieve an optimum combination of low levels of combustion chamber smoke and well-developed burning of the propellant slabs (versus the igniter) requires experimental determination of the most suitable slab dimensions and the optimum time for taking the hologram during the burn.

In an earlier investigation, Faber [Ref. 1] was partially successful in meeting these goals. He used free-standing, side inhibited slabs pressed between supporting blocks.

Window ports in the support blocks provided the viewing area. Although some holograms were successfully obtained, the window ports and associated window-protection shutters significantly altered the combustion environment during the holographic recording. In addition, side burning of the slabs often occurred when the inhibitor thickness was kept thin to minimize smoke/char production.

III. EXPERIMENTAL EQUIPMENT AND PROCEDURES

A. INTRODUCTION

The first attempt to improve the 2-D motor construction procedures used by Faber [Ref. 1] consisted of bonding the propellant slabs between two pieces of Plexiglas. In addition, a very small hole (0.125 inches in diameter) was included through which the laser beam could pass without interference with the Plexiglas. It was hoped that by bonding the propellant to the Plexiglas that erratic burning would be minimized when using minimum amounts of inhibitor. The small holes were also used to minimize the disturbance created when the window protection shutters were raised just before laser firing [Ref. 1].

Initial tests indicated that the erratic burning problem was eliminated. However, the 2-D motor flow was still strongly influenced by the side hole/window shutters.

A change was then made from Plexiglas to glass side plates because the latter did not pit and erode nearly as much as the former. Consequently, a hole through the combustion chamber was not necessary. Eliminating the hole provided a smooth gas flow along the length of the slab and also eliminated the need for shutters, since the smoke and by-products no longer vented directly onto the optical windows.

The glass almost always cracked. However, high-speed color motion pictures of the burning motor showed that the cracking usually occurred at the end of the burn, upon cooling. With glass sides, the major problems were combustion product deposits on the inner surface and/or excessive smoke created when the propellant slabs were too thick. Solutions investigated were (1) a thicker coating of RTV (inhibitor) between the propellant and the glass (this provided better thermal protection for the glass but more inhibitor char), (2) different glass thicknesses, (3) a smaller piece of propellant as the igniter, (4) inhibiting some of the igniter surfaces to produce a slower pressure/temperature rise and (5) the use of borosilicate glass.

B. EQUIPMENT

1. Laser

The laser system used was a pulsed ruby laser built by TRW, Inc., under contract to the Air Force Rocket Propulsion Laboratory. It is described in Ref. 2. The system is composed of a Q-switched oscillator, ruby amplifier, beam expanding telescope, alignment autocollimator, low-power helium-neon pointing laser, coolant system and pump, capacitor bank and associated power supplies. The wavelength was 0.6943 microns and the output beam diameter

was approximately 1.25 inches. A one joule pulse with a pulse length of 50 nanoseconds was used throughout this investigation. The laser system is shown in figures 1 and 2.

2. Holocamera

The holocamera, also designed by TRW, Inc., is completely described in Ref. 3. It was used to expose the holographic plate during the recording process and to support the plate during the reconstruction process. AGFA-GEVAERT 8E75 HD holographic plates were secured using a kinematic plate holder mounted in a removable light-tight box. The plate was positioned near the focal plane of a pair of plano convex lenses through which passed the image to be recorded. The apparatus is shown in figure 3.

3. Hologram Reconstruction

During image reconstruction, the developed holographic plate was reattached to the plate holder and returned to the removable holocamera box. Rear illumination was provided by a Spectra Physics model 165-11 krypton-ion CW gas laser, at an angle of approximately 60° with the plate normal, shown in figure 4. Output was one watt at a wavelength of 0.6471 microns. A variable power microscope was used to directly view the hologram. In order to minimize speckle, the reconstructed image was positioned on a rotating mylar disc [Ref. 4]. The latter was located at the

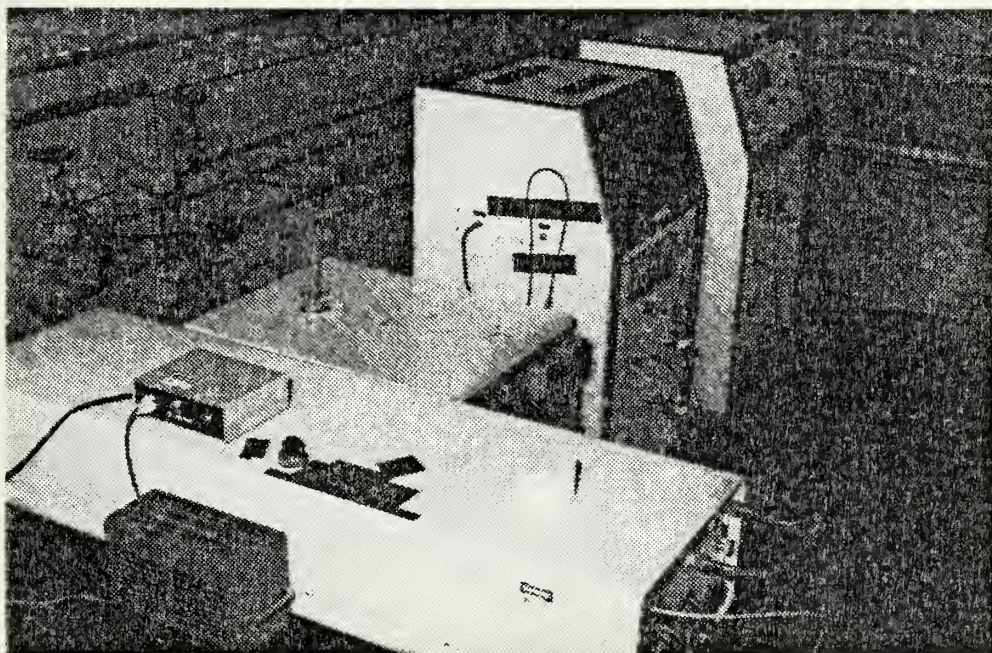


Figure 1. Q-Switched Pulsed Ruby Recording Laser

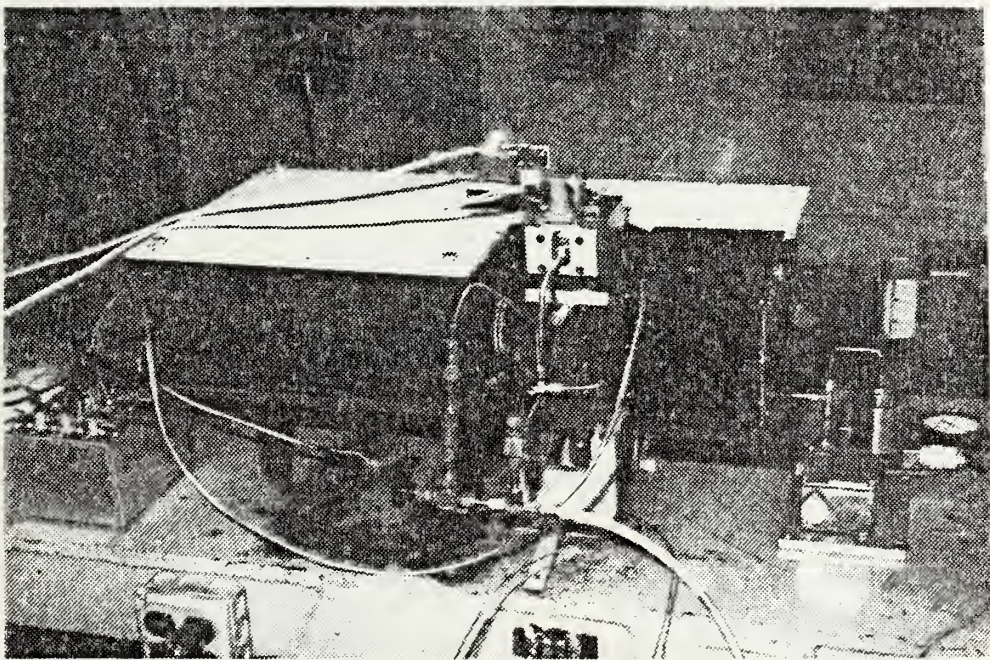


Figure 2. Lens Assisted Holographic System

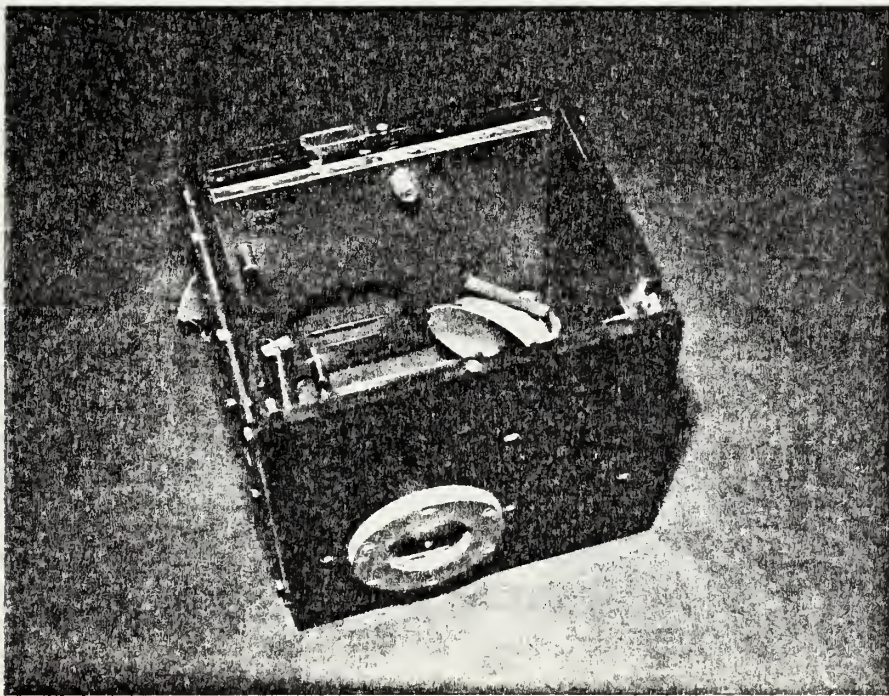


Figure 3. Holocamera Box

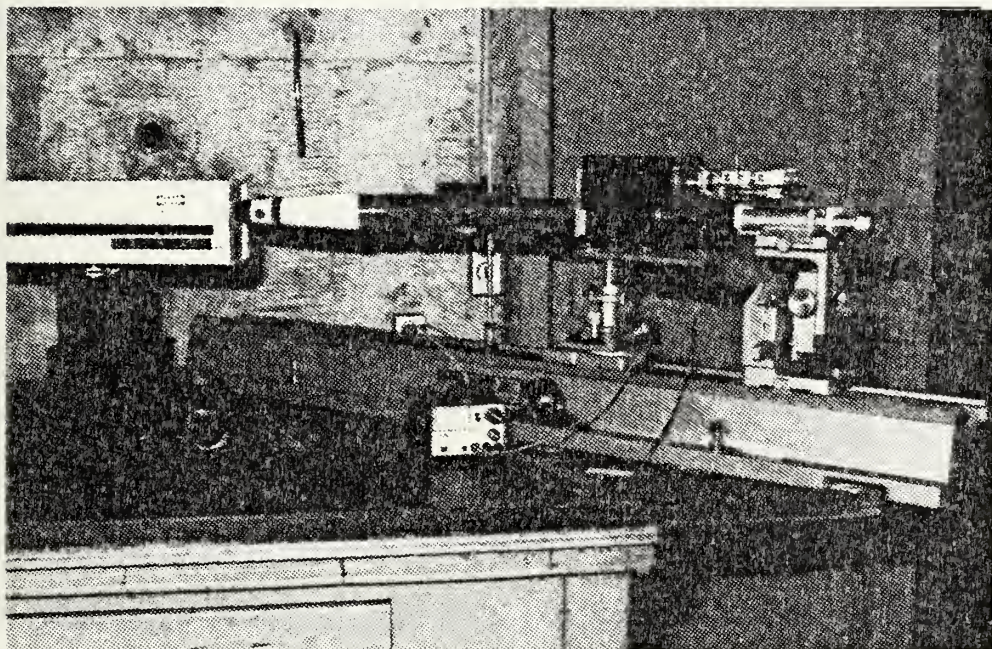


Figure 4. Holographic Reconstruction Apparatus

focal point of the observation microscope. Photographs of the reconstructed scene were made using a 35mm camera mounted to the microscope eyepiece.

4. 2-D Motor

The 2-D motors had two opposed slabs, end and side inhibited with a thin coating of General Electric Hi-temp gasket (red RTV). Motors used initially were designed to have the slabs contained in a Plexiglas tray and lid assembly, which acted as the casing. The two pieces were bonded with ethylene dichloride to form a one-piece unit, which also contained a small piece of motor propellant for an igniter. The Plexiglas motor is shown in figure 5.

The second 2-D motor design used two plates of glass, plus RTV filler to form the seal which contained the propellant and the igniter. The RTV used as an end and side inhibitor also bonded the glass to the propellant slabs. Propellant measurements are shown in figure 6 and an assembled motor is shown in figure 7. Propellant thickness varied from 0.030 inches (0.75mm) to 0.120 inches (3mm).

For the Plexiglas motors, the combustion bomb was not modified from the configuration used by Faber [Ref. 1], except that window nitrogen purge was not used and the shutter blocks were modified to move the optical windows and shutters close to the motor.

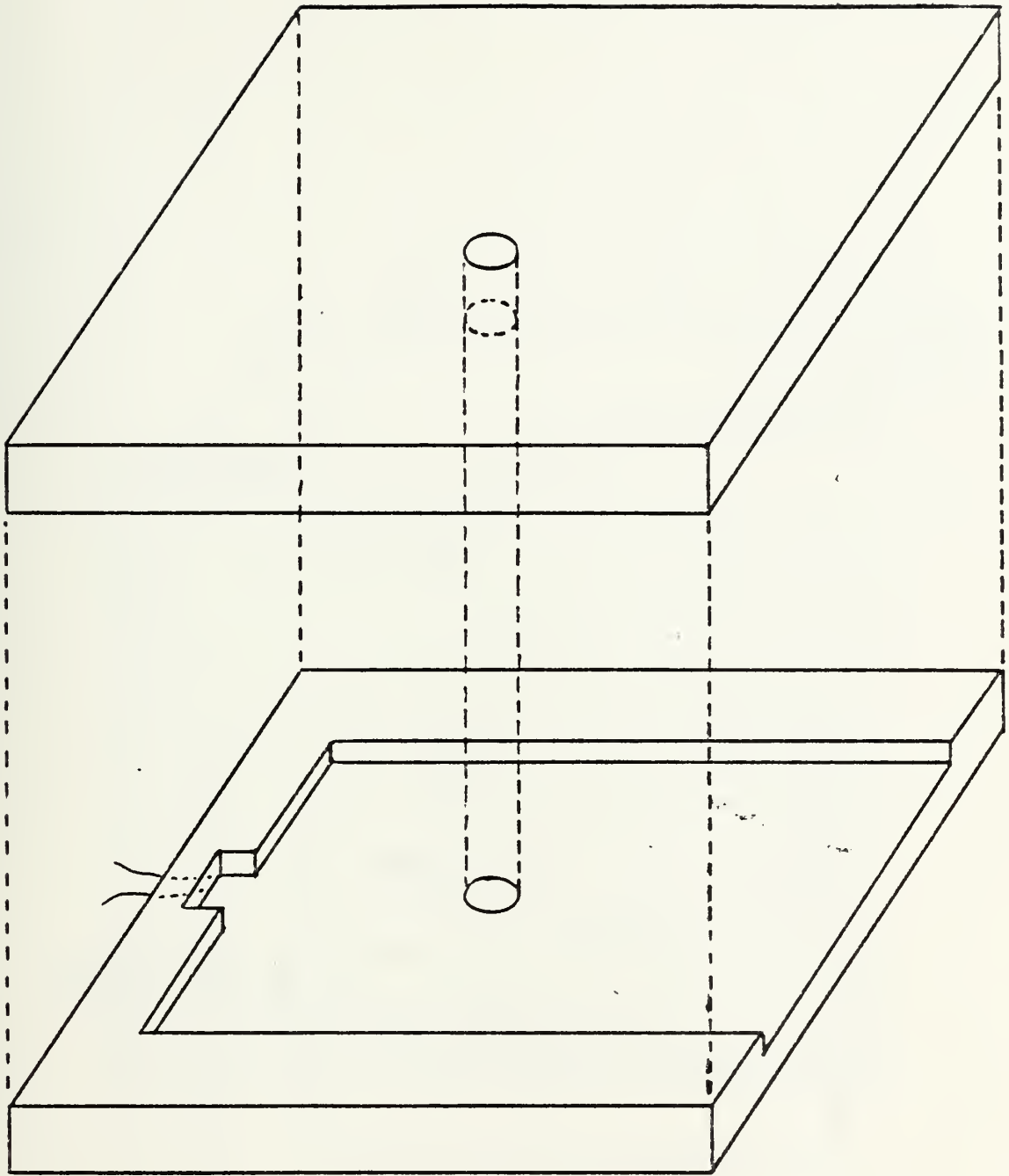
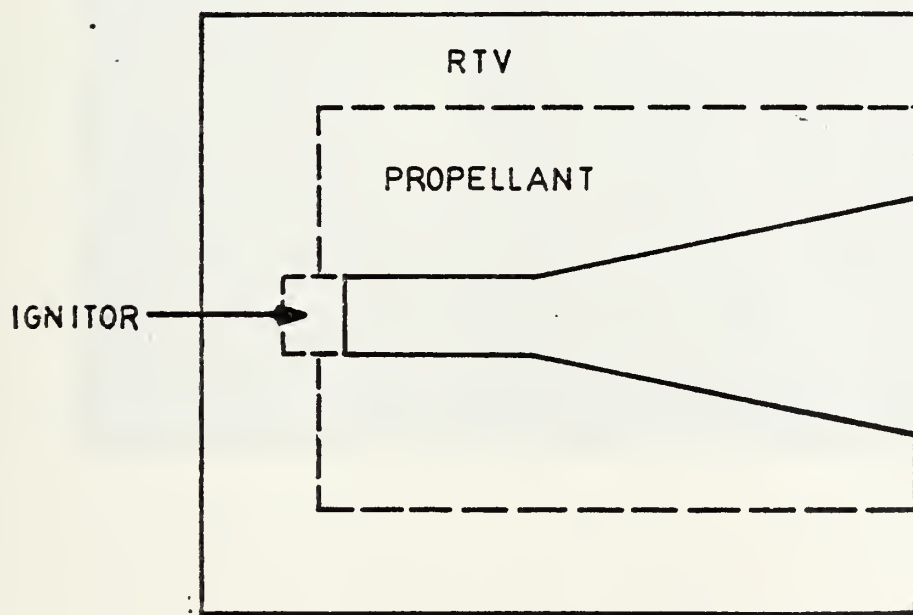
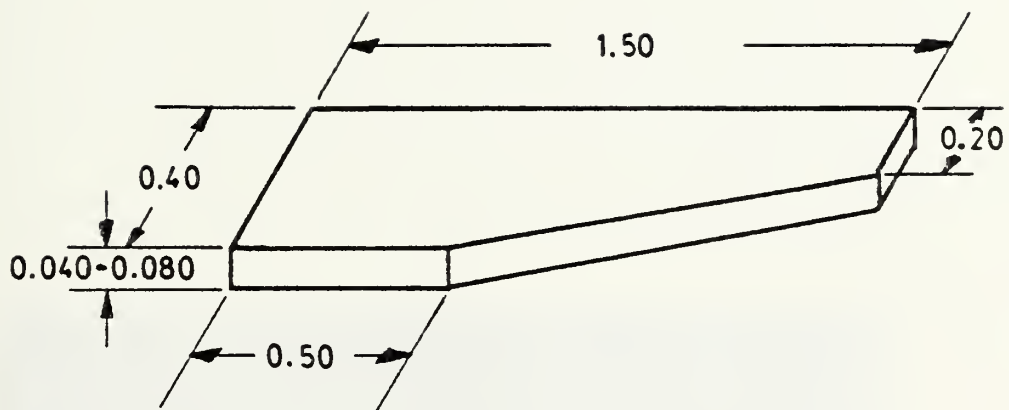


Figure 5. Schematic of Plexiglas Motor Casing



(All Dimensions in Inches.)

Figure 6. Propellant Slab Dimensions

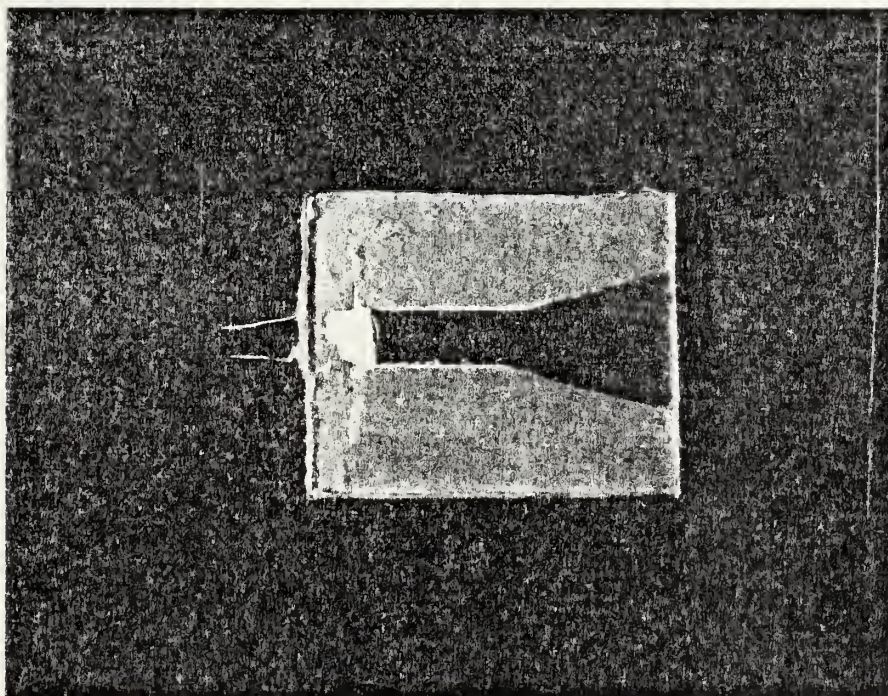


Figure 7. Propellant Mounted Between Glass Plates

If the volume of the shutter, plus the volume between the shutter and the viewing port, are significant in comparison to the combustion bomb chamber volume, shutter retraction will disturb the flow and cause combustion products to collect on the viewing ports. The shutter block/side plate modifications significantly reduced flow disturbance due to shutter retraction but the side holes continued to cause flow anomalies in the region of the scene beam.

When the glass motor casings were used, the retractable shutters, the solenoid and the microswitch were all removed from the combustion bomb, shown in figure 8. Laser firing, previously initiated by microswitch closure, was accomplished after a specified time delay from ignition. Removal of the shutter apparatus significantly reduced the set-up time and significantly increased the reliability of the system.

The laser, the holocamera, and all other components were unchanged from those used by Faber [Ref. 1].

C. PRE-FIRING PREPARATION

The propellant was rough cut to slightly oversized dimensions, then hand sanded to the desired size. RTV was applied to the sides of the slab to act as an inhibitor and to bond the motor to the side plates, either Plexiglas or

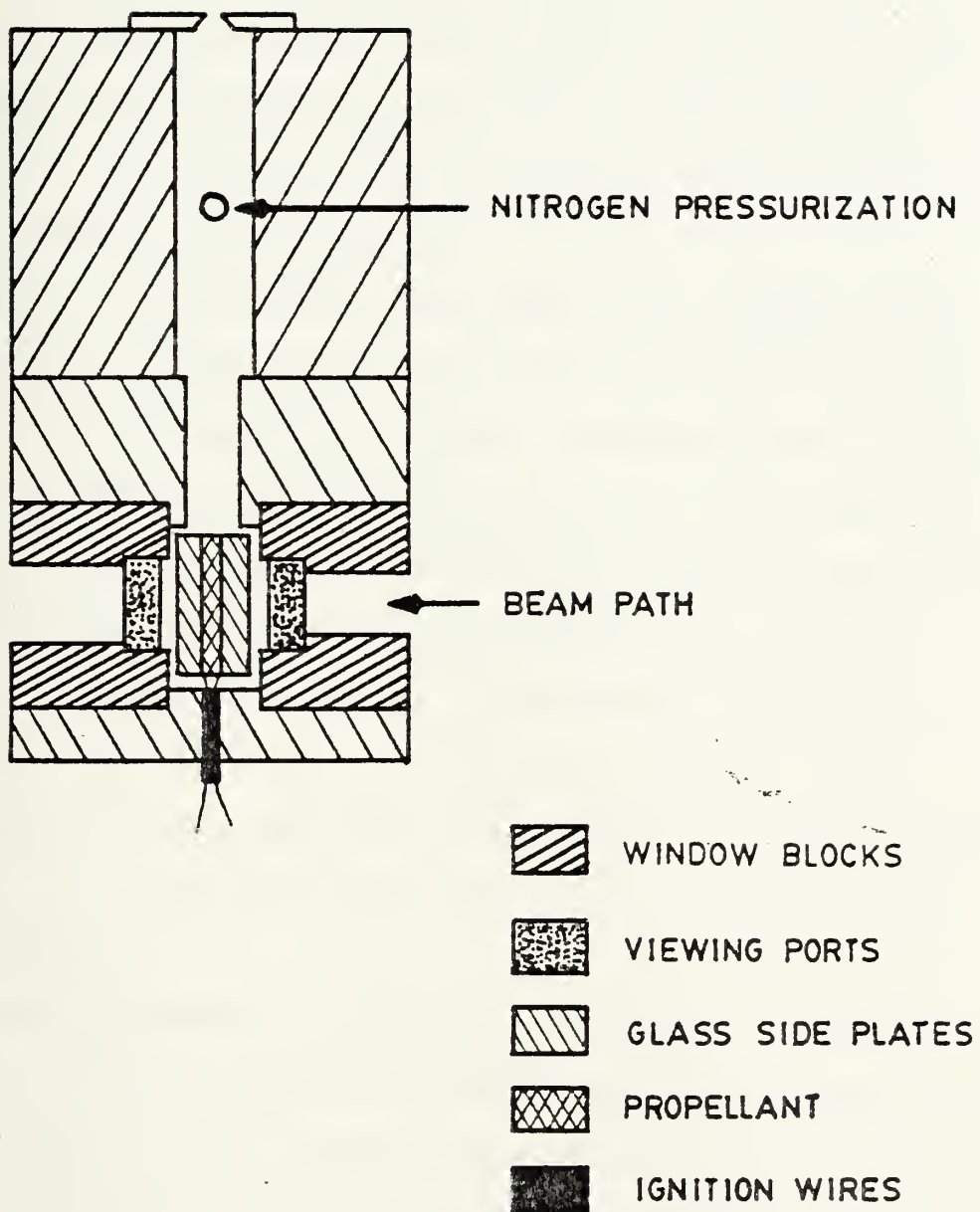


Figure 8. Schematic of Combustion Bomb

glass. With the Plexiglas, an 0.008 inch diameter nichrome wire was run through one of two holes at the head-end of the tray, looped around a small piece of slab propellant and run back through the other hole. This igniter arrangement was also used in the glass motors except that RTV held the nichrome wire in place.

The plexiglas motors were made with a fixed overall thickness of 0.305 inches to fit snugly against the shutter blocks. Propellants of varying thicknesses were accommodated by cutting different tray depths in the Plexiglas. Since the total thickness of the glass motors depended upon a combination of both glass and propellant thickness, gasket shims were bonded to the outside of the glass to ensure a snug fit against the shutter blocks. Later versions of the glass motors were bonded with quick-drying epoxy to the support blocks and did not require gaskets for support.

After attachment to the support blocks, the motor was inserted into the combustion bomb and the nichrome wire was soldered to the ignition wire which exited the bottom of the combustion bomb. The first of several continuity and grounding checks were made at this time.

With the motor mounted and wired in the combustion bomb, the shutter blocks and remaining hardware to seal the bomb were attached.

Since the burning propellant only provided about 10-20% of the desired combustion chamber pressure, a nitrogen pressurization system was used. (It was not related to the window nitrogen purge system which had been removed.) The nitrogen entry point was well downstream of the motor in order to minimize disturbance to the flow exiting the 2-D slab motor.

After the nitrogen pressure was set and turned off, another continuity and grounding check was made. Occasionally, combustion products from the previous firing, which were not accessible during cleaning, would become dislodged and interfere with the firing circuit.

Holocamera preparation required ensuring that the box and mirrors were clean. The proper reference beam neutral density filter had to be selected to provide the correct scene/reference beam intensity ratio during combustion. A 0.28 transmittance filter was found suitable for most experiments. Laser and mirror alignment were checked prior to each run to ensure that the scene and reference beams were exactly overlaid on the holographic plate and that the scene beam passed through the correct position in the motor.

After the remaining power lines and instrumentation equipment were attached, a final continuity/grounding check was made and the motor was ready for firing.

D. MOTOR FIRING SEQUENCE

The control room contained a Honeywell Visicorder which provided a time record of the entire sequence of events. A typical firing sequence for a Plexiglas motor was as follows:

1. Check electrical connections.
2. Open the reference beam shutter in the holocamera.
3. Set the laser capacitor bank to the desired firing voltage, normally 22.0 KV.
4. Start the Visicorder.
5. Charge the laser capacitor bank.
6. Turn on the nitrogen pressurization (set to 80-90% of desired chamber pressure).
7. Close the motor fire switch.
8. Propellant ignites and time delay is initiated.
9. At expiration of time delay, window shutter solenoid is energized, retracting shutters.
10. At end of shutter travel, laser fire microswitch is closed, simultaneously firing laser and opening holocamera shutter.

For the glass motors, the firing sequence was identical except that at step 9, the scene-beam shutter opened and the laser fired at the end of the time delay.

E. HOLOGRAM PROCESSING

The exposed holographic plate was removed from the holocamera in a dark room and developed as follows:

1. Immersed in Kodak D-19 developer for 90 to 210 seconds and inspected periodically under a Kodak safelight.
2. When a satisfactory opacity was obtained, the plate was immersed in Kodak "Stop Bath" for 30 seconds, then rinsed in fresh water.
3. Kodak "Hypo-fix" was used to set the image. Processing time was 5-7 minutes.
4. Fresh water rinse for 10-15 minutes.
5. Immerse in Kodak "photo-flo" for one minute.
6. Air dry for 2-3 hours.

IV. RESULTS AND DISCUSSION

A problem unique to the Plexiglas casings was keeping the combustion products and smoke from collecting on the surfaces of the optics through which the laser beam passed. The combustion process eroded and scratched the inner Plexiglas surfaces to an extent that they became translucent. Therefore, 0.125 inch diameter holes were drilled through the Plexiglas to provide a clear beam path. Unfortunately, the holes also allowed combustion products to vent directly onto the glass windows of the combustion bomb, rendering them opaque. The retractable shutters [Ref. 1] which covered the viewing ports and the windows were moved as close as possible to the Plexiglas to both protect the windows before laser firing and to minimize the free volume of the window ports.

Although the shutters kept the windows clean, and the laser fired at the desired time during the burn, the use of Plexiglas side plates failed to produce high quality holograms. Smoke in the beam path hole appeared to have been the impediment. With no holes, the smoke thickness would have been equal to the propellant thickness, 0.030 to 0.120 inches. When the smoke filled the hole, however, a column approximately 0.305 inches long (Plexiglas

tray thickness) was presented to the beam. Even early in the burn, when the smoke density was a minimum, the laser could not penetrate the combustion bomb. The primary contribution of the Plexiglas side plates was the development of motor preparation procedures which significantly reduced the motor preparation time and complexity.

The use of glass was a major improvement not only in the reliability and ease of preparation of the motor but also in the quality of the obtainable holograms.

Initially, 0.047 inch thick slide glass was used and it yielded excellent results with low pressure and very thin propellant slabs, despite the presence of cracks.

Ordinary window pane glass of 0.156 inch and 0.219 inch thicknesses was used next. These tests were not successful because of what appeared to be too short a time interval between fully developed slab burning and the onset of glass cracking.

Even though the onset of glass cracking could not positively be determined, two solutions were tried in an effort to eliminate or reduce it. The ignition source was modified to give a slower pressure and temperature rise; by inhibiting several surfaces with RTV and by re-routing the ignition wire so that it was not in contact with as much igniter surface. Second, a thicker layer of RTV

was applied to the slab sides of the propellant to provide the glass with more insulation from the propellant flame. Neither modification noticeably altered the crack propagation.

Besides cracking, combustion product deposits on the inner surface of the glass also interfered with laser beam penetration. By the end of a burn, all glass was either translucent or opaque. How quickly the deposits accumulated was not known, but their presence underscored the importance of taking the hologram as early in the burn as possible. Since an excellent hologram had already been made using the slide glass, which exhibited similar deposits, it was felt that cracking or thick smoke, and not combustion product deposits, was the prime obstacle.

With the introduction of borosilicate glass as a side panel material, cracking became almost non-existent. Rather than a random crack pattern which completely covered the area between the slabs, a single crack would often run the length of the glass, following the pre-ignition shape of the propellant surface. Both pieces of glass always cracked (except for one WGS-5A burn).

Regardless of when cracking occurred, it did not degrade the quality of the hologram. Possible melting or heat induced distortion of the inner surface of the glass, however, may have degraded hologram quality. Post-burn

examination of all borosilicate motors revealed extensive areas of melted or distorted glass. The thickness of this region, measured normal to the inner surface, was approximately 0.015 inches at the head end, growing linearly to approximately 0.035 inches at the nozzle. Early borosilicate cases, which had thinner coats of RTV to minimize debris in the hologram, appeared to have sustained more melting. This was a relatively subjective observation, since the varying degrees of distortion made the determination of a melted area boundary difficult.

Combustion products also collected on the inner surface of the borosilicate. This problem was felt to be more serious than with the slide or pane glass because the borosilicate was probably more prone to collecting debris when it was soft and melting.

Despite the drawbacks of borosilicate, it enabled excellent holograms to be obtained.

Figure 9 is a photograph of a reconstructed hologram which contained the 0-80 screw used for a particle sizing reference. Figures 10 through 14 are photographs of the reconstructed holograms of burning propellant.

Several observations can be made from the results concerning the present technique for obtaining holograms in the cross-flow environment. Thin ($\approx .040$ inches)

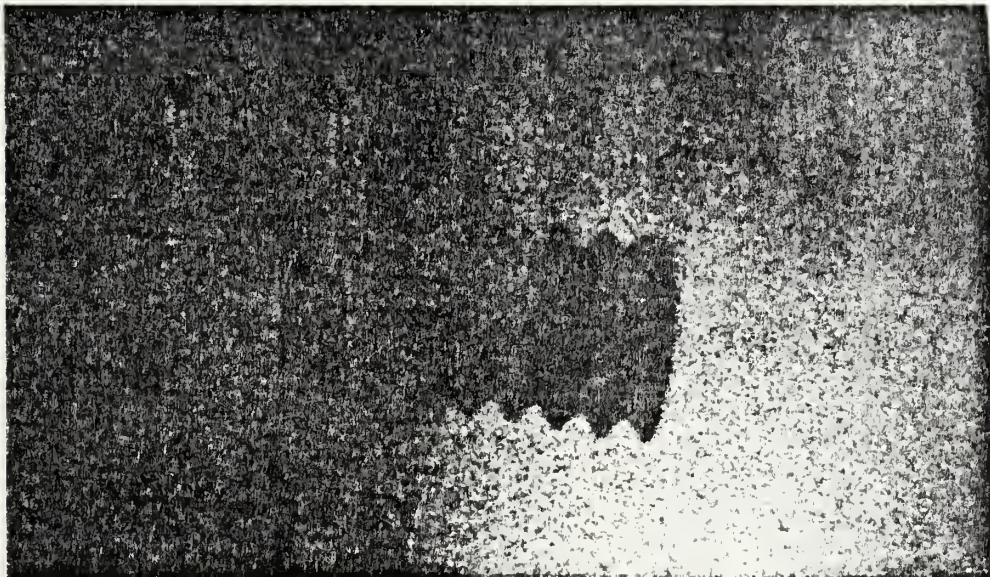


Figure 9. Photograph of 0-80 Screw
from Reconstructed Hologram.

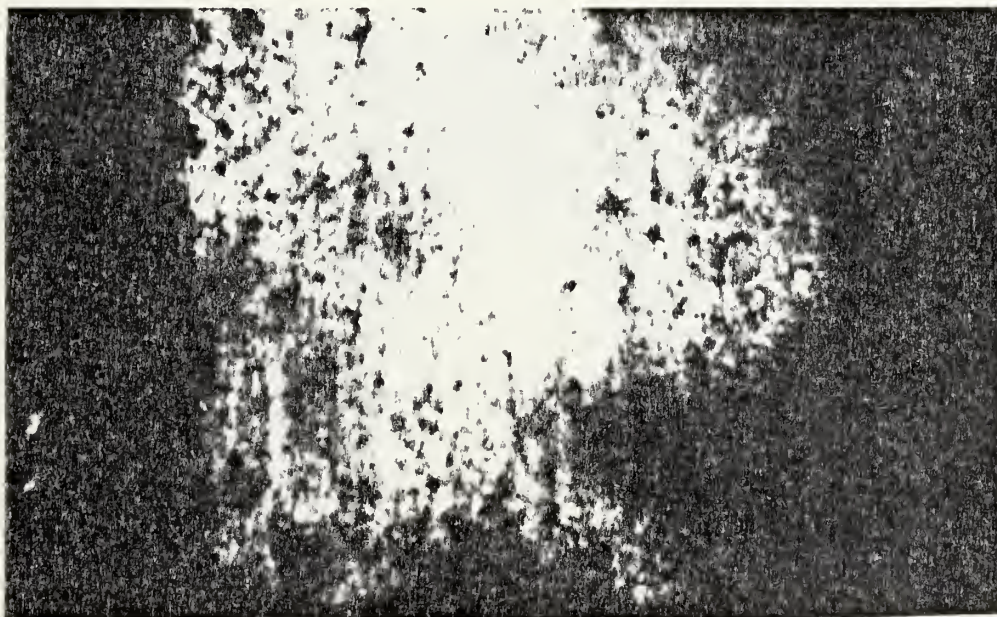


Figure 10. Photograph of Reconstructed Hologram of WGS-7A
Burned at 390 PSIA, 0.047 Inch Thick Slide Glass

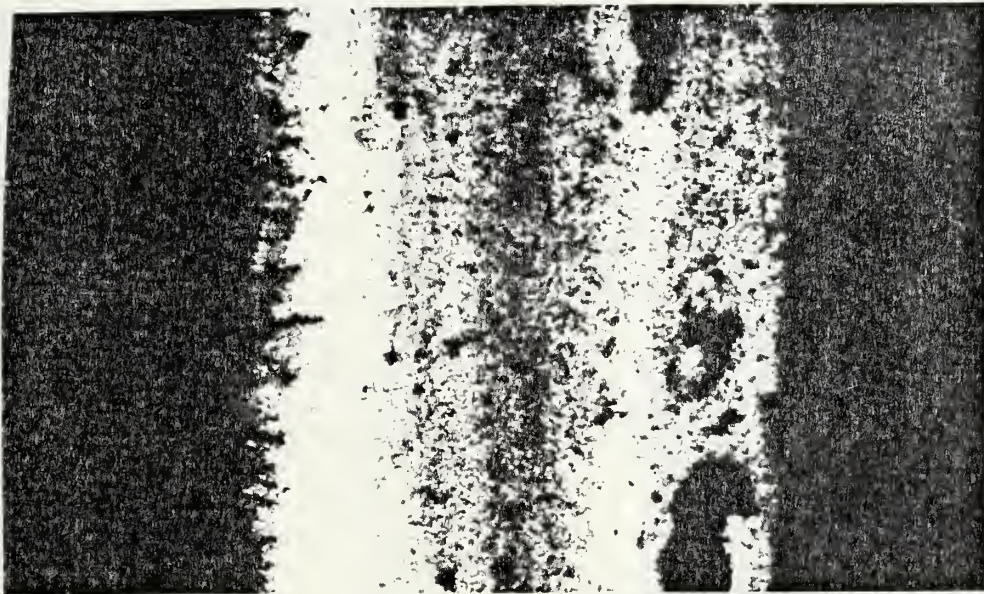


Figure 11. Photograph of Reconstructed Hologram of WGS-7A
Burned at 615 PSIA, 0.219 Inch Thick Borosilicate

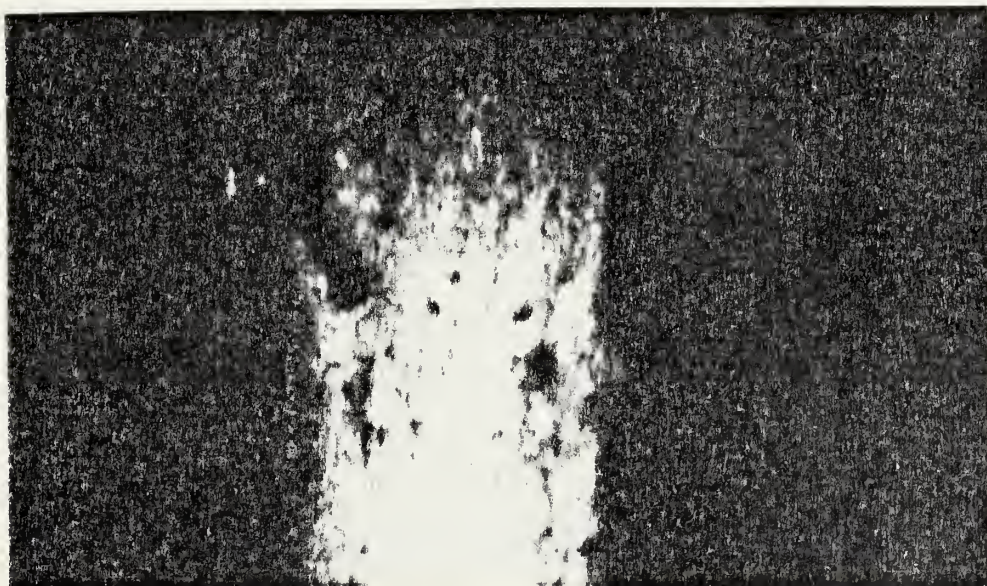


Figure 12. Photograph of Reconstructed Hologram of WGS-7A
Burned at 500 PSIA, 0.219 Inch Thick Borosilicate

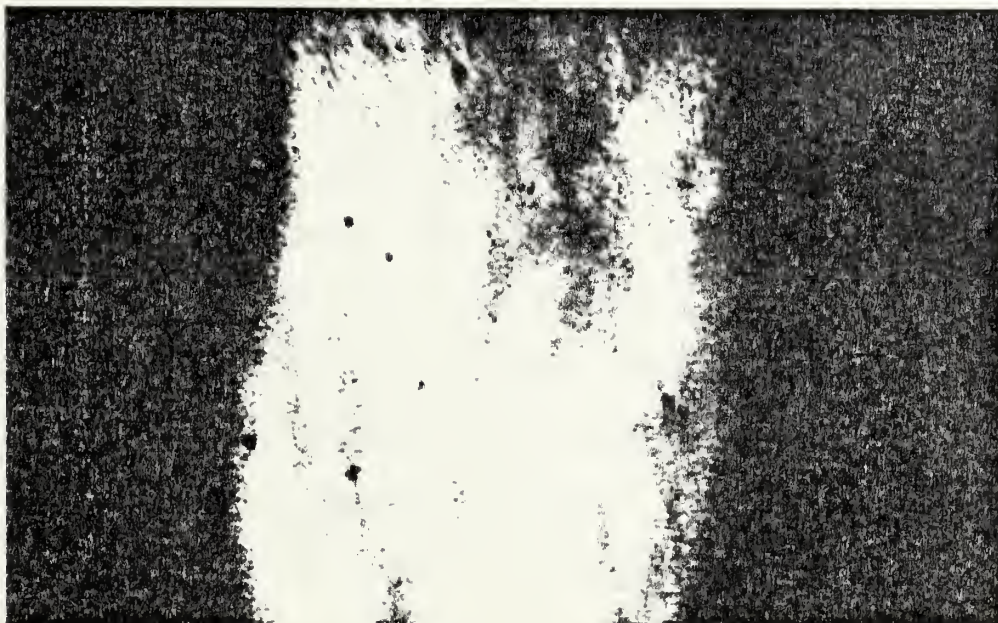


Figure 13. Photograph of Reconstructed Hologram of WGS-6A
Burned at 575 PSIA, 0.219 Inch Thick Borosilicate

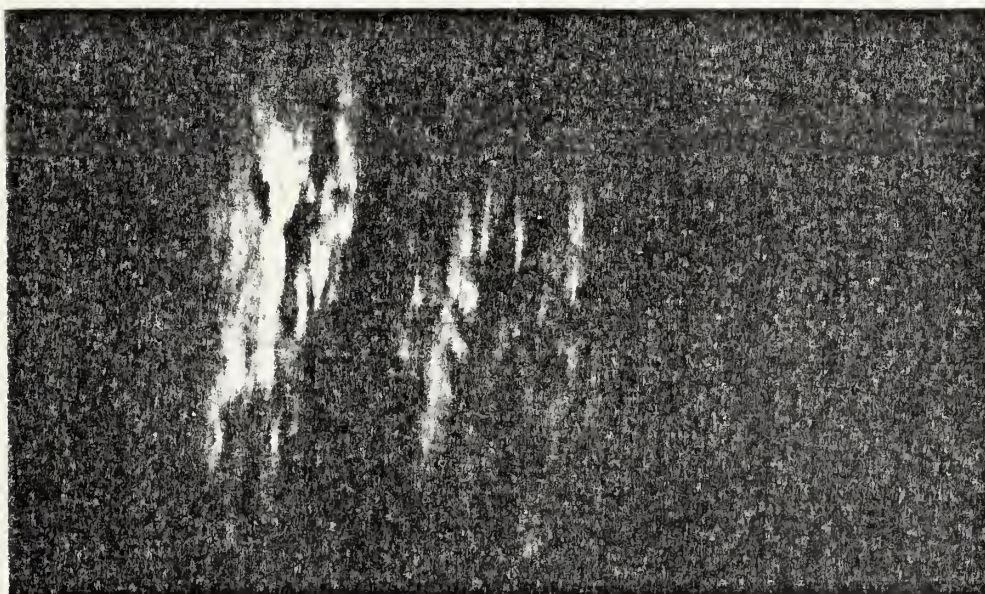


Figure 14. Photograph of Reconstructed Hologram of WGS-5A
Burned at 535 PSIA, 0.219 Inch Thick Borosilicate

propellant slabs and low pressure (≈ 400 psi) allow good quality holograms to be obtained through much of the burn if cracking is not severe. Holograms can be obtained at higher pressures (>500 psi) and with thicker slabs ($\approx .080$ inches) if the laser is fired very soon after steady-state burning is achieved. The smaller the aluminum powder size in the propellant, for a given mass loading, the more difficult it is to obtain a hologram. This is due to the higher number density of particles and more uniformly distributed smoke/very small particles.

Table I presents the propellant compositions.

TABLE I

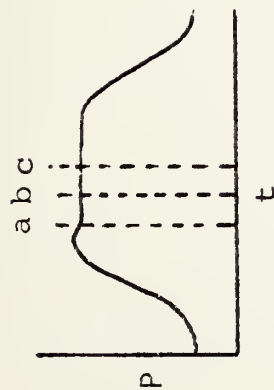
PROPELLANT COMPOSITION

PROPELLANT DESIGNATION	BINDER % WEIGHT	OXIDER % WEIGHT	METAL % WEIGHT	MEAN METAL DIAMETER, MICRONS
WGS-7A	HTPB 12	AP 83	AL 05	23-27
WGS-6A	HTPB 12	AP 83	AL 05	45-62
WGS-5A	HTPB 12	AP 83	AL 05	75-88

Table II summarizes the test conditions under which good holograms were obtained.

TABLE II

SUMMARY OF TEST CONDITIONS



	Propellant Pressure (psia)	Time Delay* (in)	Propellant Thickness (in)	Casing Material and Thickness (in)	Hologram Figure Number	Remarks
WGS-7A	390	a	0.037	Slide Glass 0.047	10	Excellent holo- gram. Propellant burning.
WGS-7A	615	a	0.050	Borosilicate 0.219	11	Excellent holo- gram. Very early in the burn.
WGS-7A	500	a	0.080	Borosilicate 0.219	12	Excellent holo- gram. Early in the burn.
WGS-7A	590	c	0.070	Borosilicate 0.219	none	No hologram. Too much smoke.
WGS-6A	575	a	0.070	Borosilicate 0.219	13	Excellent holo- gram. Early in the burn.
WGS-5A	535	c	0.070	Borosilicate 0.219	14	Good hologram. Much smoke, limited field of view.

*See Pressure/Time Graph Above.

V. CONCLUSIONS AND RECOMMENDATIONS

The use of glass side plates on the 2-D motors has allowed good quality holograms to be obtained of propellants burned in a cross-flow environment. To date, pressures have been limited to approximately 600 psia and propellant slab thickness to 0.080 inches. For higher pressures and smaller aluminum sizes it will probably be necessary to use thin (≈ 0.040 inches) slabs and minimum inhibitor in order to minimize smoke.

The use of glass sides also eliminated the need for combustion bomb window shutters and greatly simplified the required combustion bomb. A new, more simply constructed bomb should be fabricated in order to minimize motor preparation time.

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